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ABSTRACT

A model of human information processing is summarized and discussed in terms of the implications of the model and its associated technologies for curriculum research and development. Description of the model focuses on its input and output systems and its memory systems, i.e., long-term memory (LTM). Semantic networks are described as a representation of LTM, particularly the work of Lindsay, Norman, and Rumelhart at San Diego. Curricular implications discussed include analysis of disciplinary knowledge and the use of concept maps to represent that knowledge, cognitive objectives expressing the changes intended in a student's cognitive structures or processes, curriculum organization decisions, content analysis, and finally, evaluation of student learning (particularly what is involved in answering a typical classroom or test question). Conclusions regarding the potential and actualized contributions of cognitive science for curriculum research and development are then discussed. (Author/VT)

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COGNITIVE SCIENCE: IMPLICATIONS FOR CURRICULUM RESEARCH AND DEVELOPMENT

by

George J. Posner

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ABSTRACT

This paper attempts to summarize a model of human information processing and then to identify the implications of this model and its associated technologies for curriculum research and development. The model is described in terms of its input and output systems, its memory systems and its control processes. The focus of the paper, however, is on one of its memory systems, i.e., long-term memory (LTM). Semantic networks are described as a representation of LTM, particularly the work of Lindsay, Norman and Rumelhart at San Diego. In terms of curricular implications, five areas are discussed: analysis of disciplinary knowledge and the use of concept maps to represent that knowledge, cognitive objectives expressing the changes intended in a student's cognitive structures or processes, curriculum organization decisions, content analysis and, finally, evaluation of student learning (particularly, what is involved in answering a typical classroom or test question). Conclusions regarding the potential and actualized contributions of cognitive science for curriculum research and development are then discussed.

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Cognitive Science: Implications for Curriculum Research and Development*

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As the title of this paper suggests, a new inter-discipline has been developing which promises significant contributions to education in general and to the field of curriculum in particular:

> The development of digital computers has produced powerful tools for use in the study of mental processes. Computers are information-processing systems. They can manipulate information and make decisions. Knowledge of information processing is essential if you are to understand the tools of the study of thought mechanisms. Now, before we begin, please note carefully that the mind is not a digital computer. But although the machinery is different, when it comes to the abstract, scientific principles of information processing, there are general rules that will apply, regardless of what device is being spoken of. So the science of information processing is relevant to us, even if the engineering may not always be. This science...is now being called Cognitive Science.
>
> (Lindsay and Norman, 1977, pp. 593-4)

This new science brings together people working in cognitive psychology, artificial intelligence, and linguistics to study problems concerned with the representation of meaning and the structural and processing aspects of language, knowledge and problem solving. (Rumelhart and Ortony, 1977) The aim of these researchers is to understand what is involved in intelligent behavior (Norman and Rumelhart, 1975) and, in particular, to understand how knowledge is organized to permit storage, retrieval, and utilization of knowledge, and how a person's previous experience and existing knowledge affect perception, communication,

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learning and performance of tasks. Although the fruits of this line of inquiry clearly have implications for the selection and organization of subject matter, attempts to relate these new developments to curricular concerns have been few in number.[1] However, the reports of two recent conferences[2] have pointed out clearly both curricular and instructional implications of this work (Klahr, 1976; Anderson, Spiro and Montague, 1977). These conferences (particularly the second) represent the first time noted cognitive psychologists, psycholinguists, and artificial intelligence experts such as Donald Norman, David Rumelhart, Alan Collins, Herbert Simon and John Bransford, have engaged in extended discussions with curriculum researchers and theorists such as Harry Broudy, Philip Jackson, Robert Glaser and Robert Gagné, to mention just a few of the many notable persons attending. While the focus was not just on curricular but also instructional concerns, the selection and organization of content and the consequences of these sorts of decisions for knowledge acquisition and utilization was a clear focus.

Underlying the discussions at these conferences was the notion that human beings may be viewed as processors of information. This view of human beings as information processing systems begins as a metaphor "rich in features in its own right whose relevance to the object of comparison is problematic." (Newell and Simon, 1972, p. 5) But it moves beyond its status as a metaphor as it has demonstrated its capability as a model from which detailed predictions and explanations can be made.

For some of the participants of the two conferences human information processing models suggest areas of potential curricular content, even implying curricular "oughts." For example, Norman, Gentner and Stevens (1976) view Seymour Papert's work in artificial intelligence on programs that can eliminate their own errors (i.e., "debug") as suggesting a class of curricu-

lum content to teach students: "Why do we not attempt to teach some basic cognitive skills such as how to organize one's knowledge, how to learn, how to solve problems, how to correct errors in understanding." (p. 194) Hayes (1976) and Greeno (1976) make a similar case for "direct training of cognitive skills." (Hayes, 1976, p. 238)

However, rather than examine human information processing models as a source of curricular "oughts," this paper will focus on these models for their technological use, much as the engineer uses the knowledge produced by scientists "to make goods or to establish operations," thus helping an "ought" become an "is." (Huebner, 1977, p. 69) Although the human information processing models may appear to some as useful for their insights into what man can become, I wish to focus primarily on the technological implications of human information processing models.

Let us, therefore, examine the elements of a human information processing model and then determine the extent to which such a model with its associated techniques can contribute to efforts in curriculum research and development.

* * * * *

Part I

Cognitive Science: Recent Developments.

In this major section, I will consider some current ideas about the human information processing system. First, the basic elements of such a system are described. Then one aspect of this system is considered in detail, namely, the information it has about the world and how this knowledge can be represented. Finally, issues of epistemological and psychological validity of these representations are discussed. This whole section is intended to form a backdrop for the next section on curricular applications of cognitive science.

A. The Basic Elements of a Model of Human Information Processing.

In most accounts of the human information processing system some common elements appear.

1) There is an input of information into the system through sense organs and an output by which the individual changes his original environment.

2) There is an aspect of memory, termed short-term memory (STM), which is limited in capacity to about 6 or 7 "chunks" of information (George Miller's "magical number 7 ± 2" -- Miller, 1956) and which requires constant rehearsal in order to prevent information from fading (i.e., forgetting). It is in this limited STM where calculations and other problem solving normally occur. This so-called "working memory" processes information in serial (i.e., one operation at a time) rather than parallel (i.e., several operations simultaneously) fashion according to Newell and Simon (1972).[3] The limitations of this aspect of memory is illustrated by the relative ease most people have in multiplying 53 X 7 in their heads (requiring never more than 3 chunks of information to be

stored at any one time) but the great difficulty in multiplying 53 X 45 in their heads (which requires storing as much as 6 chunks of information while performing other operations).

3) One of the most significant aspects of the system (for curriculum specialists) is long-term memory (LTM) in which people store everything they know about the world (alternatively termed the "data base"). One of the most interesting features of this data base is its seemingly unlimited capacity[4] and yet the difficulty encountered in retrieving previously stored information. Another highly significant feature of LTM is its high degree of organization. Just about everything one knows (i.e., in LTM) is related in some way to everything else one knows. No wonder that conversations or free associations that begin on one topic can end up on almost any other topic. In fact, it is this high degree of organization that has led most current cognitive scientists to rediscover and subsequently to refine the original Kantian notion of a "schema." Anderson (1977) sums up the most recent conference as follows:

> The principal concept developed at this conference was that of schema, an idea whose time has finally come...Figures such as Max Wertheimer and Sir Fredric Bartlett developed schema theories which have much in common with current formulations and, of course, Jean Piaget is still the preeminent schema theorist. Schema notions are not new on the American scene either. Witness psychologist-educators such as Bruner (e.g. 1960) and Ausubel (1963). However, just a few short years ago they were largely voices in the wilderness, out of the mainstream, ignored by many, abused by few ...Those of us with a different world view were able to "counter-argue," successfully we thought at the time...The force of the concept of schema is to direct attention to the patterning of elements. What the elements [of knowledge] are and how they interrelate cannot profitably be addressed as separate issues. (pp. 416-18)

This notion of LTM as consisting of schemata was pervasive at both conferences. Schemata are "data structures for representing the generic concepts stored in memory. They exist for generalized concepts underlying objects,

situations, events, sequences of events, actions and sequences of actions." (Rumelhart and Ortony, 1977) As Bransford and Johnson (1973) and more recently Anderson, Reynolds, Schallet and Goetz (1977) have demonstrated in a series of experiments, getting a prose passage to make sense is a matter of finding a coherent formulation for it. These studies suggest that "comprehension and, therefore, learning and memory, depend upon bringing to bear appropriate schemata." (Anderson, 1977) Thus, schema theory implies that portions of LTM function not just as a store of information but also: (a) as a format into which new information must be fit, if it is to be comprehended, (b) as a plan for directing one's attention and for conducting purposeful searches of one's environment, and (c) as a resource for filling in gaps in the information received.[5]

4) There are two sets of control processes. One set conducts searches of the data base, operates on the data base and moves information between the information stores. This set of control processes is often termed the interpretive processes. The interpretive processes play a significant role in problem solving, recall and recognition, language comprehension and computation tasks. These processes enable human beings to think deductively, inductively, analogically, and algorithmically. Clearly, without these processes most of what we know would be useless information, regardless of how well it was learned.

The other set of processes acts as a supervisor for the system making executive decisions regarding the fruitfulness of searches, the location in LTM of particular items of information, and the amount of effort required for searches and other operators. This set of control processes is termed the monitor system. If the human information processing system may be

likened to other information processing systems such as libraries, the monitor could be considered analogous to the reference librarian and card cataloguing system; the interpreter in this analogy would be the librarian or other individual who goes to the stacks to fetch books from or return books to their proper place on the shelves. (Lindsay and Norman, 1977) It is the monitor that has the capacity of metamemory -- knowing what it knows. This is easily illustrated by trying to answer the following types of questions (suggested by Lindsay and Norman, 1977):

What was Rousseau's telephone number?

You refuse to answer this question because you know that telephones had not been invented before Rousseau died.

What was Dewey's telephone number?

You still refuse to try to retrieve the number. You know that you don't know. How do you know this?

What is the telephone number of your best friend?

As Lindsay and Norman point out:

> . . .when asked to recall something, you do not start off blindly searching the data base. Rather, the monitor instructs the interpretive processes to analyze the question to see whether you are likely to find anything. On the basis of this preliminary analysis, you may conclude that there is no sense in even attempting to recall the data. Maybe the information does not exist. Maybe the information exists but you know it is not in your memory. . . Maybe you think you might be able to retrieve the information if you tried, but it would require too much effort to be worth the bother. (1977, p. 370)

One of the most significant contributions of recent developments in cognitive science is the increased precision with which we are now able to

specify the cognitive structures and processes required to perform tasks. This increased precision derives from the efforts of cognitive scientists to simulate intelligent behavior on a computer. Computer simulations require the complete specification of both the data base and the procedures necessary for performing any task characteristic of intelligent functioning. If any aspect of the data base or procedure for utilizing the data base is omitted the program simply will not work or, at least, will not accurately simulate human behavior. Computer programs that successfully simulate human performance of tasks are candidates for psychological models. Such plausible models (and there are likely to be several plausible models for any given task performance) are then subjected to psychological validation of the sort described later in this paper.

As mentioned earlier, most cognitive psychologists believe that what a person already knows and how his knowledge is organized (i.e., his schemata) are primary determinants of what he perceives, what he can do, and how he thinks (cf. Ausubel, 1968). Thus, an important area of research for cognitive scientists has been the representation of knowledge stored in LTM.

B. Representation of Data Base Using Semantic Networks.

Recent research in cognitive science has been marked by a proliferation of techniques for representing information stored in LTM (i.e., the individual's data base). However, the majority of these new techniques have adopted a common approach. This common approach can be characterized by a reliance on the use of networks to represent what an individual knows. A network consists of a set of nodes or points (a, b, c. . .n) interconnected by a set of labeled directed lines or pointers (R_1, R_2. . .R_n) as depicted in Figure 1, below.

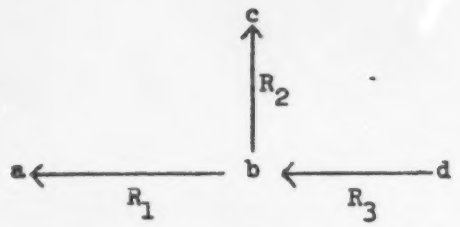

Figure 1. A generalized example of a simple network showing nodes a, b, c and d interconnected by directed lines, R_1, R_2, and R_3.

The basic unit of such a network is termed a "triple" consisting of two nodes connected by a relationship. Nodes may represent attributes, objects, actions, or classes of objects or actions. Each line in such a network is "bi-directional but not symmetrical." (Norman and Rumelhart, 1975, p. 35) That is, the linkage between two nodes may be interpreted as a given R or in the opposite direction by the inverse of R. For example, if node a represents the concept "animal," node b represents the concept "mammal" and R represents "subset," then inverse-R represents "superset" as follows:

mammal $\xrightarrow{\text{subset}}$ animal, and

mammal $\xleftarrow{\text{superset}}$ animal

or more generally

a $\xrightarrow{R}$ b, and

a $\xleftarrow{\text{inverse-R}}$ b

Many approaches to network representation of knowledge have been developed by cognitive scientists. These approaches differ from one another in what types of information are represented by the nodes and the lines constituting the network. Tulving (1972) distinguished between two classes of information stored in LTM he termed episodic and semantic. Episodic memory refers to memory of events as they were experienced; semantic memory refers to memory of concepts

abstracted from experience and the definitional structure of interrelated concepts.[6] Semantic memory is represented by semantic networks containing concepts (e.g., dog) or instantiations of concepts (e.g., this dog or Fido) at nodes and relationships between concepts (e.g., class membership) as labeled directed lines.

In our work at Cornell we have found that a limited number of relationships between concepts find application in semantic networks across subject matter areas. Generally these relationships derive from logic. These widely applicable relationships can be abbreviated for the sake of economy. Table 1, below, lists some of these general relationships and the abbreviations we have found useful.[7]

Abbreviation	Explanation of relationship	Example
ISA	is an instance of	Fido $\xrightarrow{\text{ISA}}$ Dog
subclass	is a subclass of the class of (class membership)	Beagles $\xrightarrow{\text{subclass}}$ Dog
HAP	has as a part (part-whole)	Dogs $\xrightarrow{\text{HAP}}$ tail
property	is a property of	Beagles $\xrightarrow{\text{property}}$ droopy-eared

Table 1. A list of some general relationships found in many subject matter areas.

Of course, there are many relationships particular to specific subject matter areas such as "connects to" (anatomy, auto mechanics), and "is the sum of" (mathematics). Others apply to several, though certainly not all, subject matters such as "causes," "varies inversely as," and "represents." We have found that within a particular subject matter, the total number of relationships necessary for representing knowledge is rather limited making it feasible to construct simple dictionaries of relationships for each subject matter area,

each with probably no more than one or two dozen entries. Figure 2, below, depicts a semantic network for a portion of cognitive science as it has been described thus far in this paper.

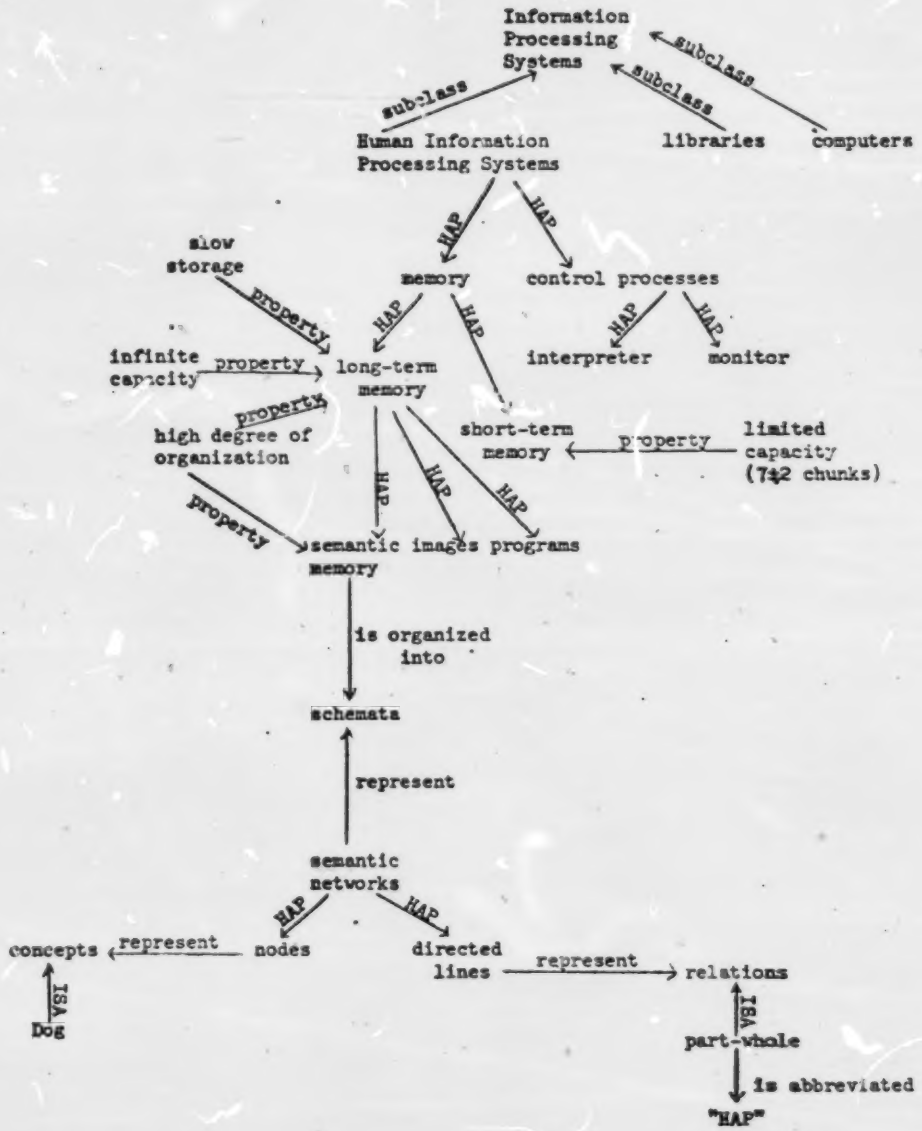

Figure 2. A Network Representation of a Portion of Cognitive Science. Note that the network represents the major elements of the model of human information processing, but is incomplete with regard to the model's details. Table 1 serves as a partial key to the network's abbreviations.

In episodic memory many aspects of the experienced event need to be taken into account: the action, the agent (who causes the action), the objects (things being acted on), the recipients (who receive the effect of the action), the time (when the event occurred), the location (where the event occurred), the instrument (the thing involved to cause the event), and the logical conditions (between two events, such as "because" and "only if"). (Fillmore, 1968)

Episodic and semantic memories do not exist as separate cognitive entities but are highly interrelated. The distinction is between two classes of information contained in the same data base of the human information processing system. Figure 3, below, provides a representation of the following information a hypothetical student has about birds (note the interrelation of semantic and episodic memory):

All animals reproduce, eat food and breathe.
A bird is an animal that has feathers.
The emu is an Australian bird that does not fly.
A canary is a yellow bird that whistles.
Ian's canary, "Sam," escaped from its cage yesterday because he left the door open.

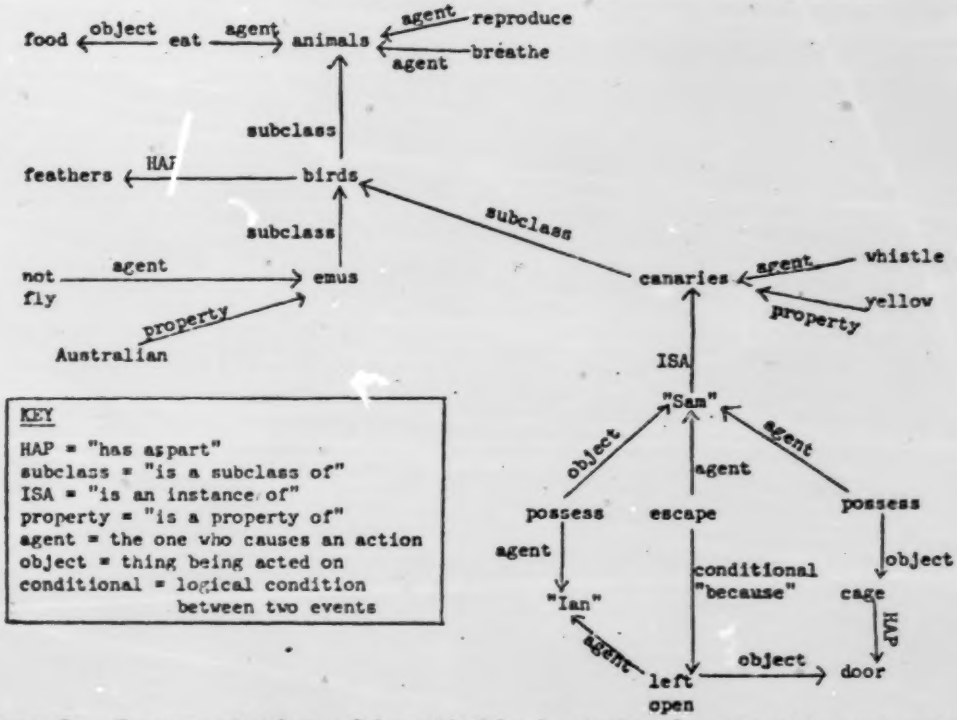

Figure 3. Representation of hypothetical student's semantic and episodic memory of birds. (Adapted from Atkin, 1977.)

The interrelation of semantic and episodic memory has caused researchers such as Norman and Rumelhart (1975) to propose what they term "active structural networks." In such networks both logical relations among concepts (as in Tulving's semantic memory) and conditions of events (as in Tulving's episodic memory) are represented within the same network. We have adapted these active structural networks for use in representing the major propositions of certain subject matters. For example, the following propositions from earth science can be represented in a "radiative balance" schema such as that depicted in Figure 4, below:

The earth is in a state of radiative balance.
When something is in radiative balance it emits and absorbs approximately equal amounts of energy.
The earth absorbs its radiation from the sun.
The sun emits a lot of radiation into space only 5×10^{-10} of which is absorbed by the earth.
The earth emits its radiation into space.

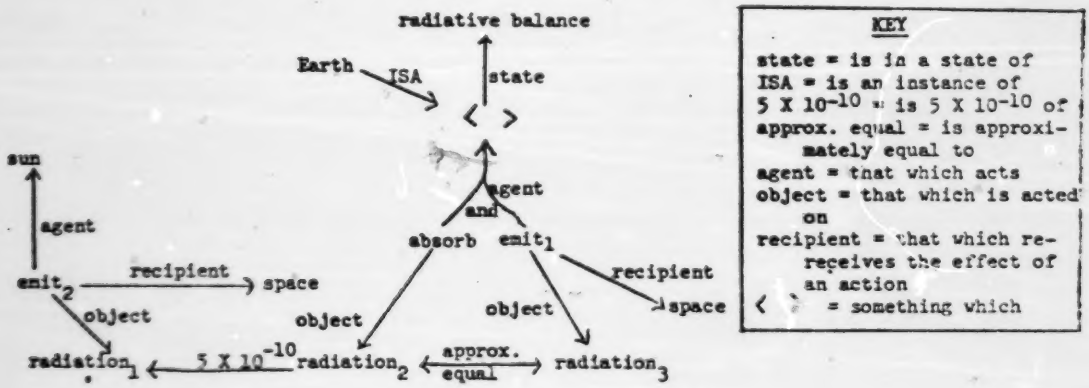

Figure 4. A "Radiative balance" schema.

The reader may have noted that within this one schema we can specify other schemata. There is an absorption schema and two emission schemata. Each of these schemata could have been decomposed and shown to include other schemata. Thus, it should be clear that schemata embed other schemata, each successively embedded schema providing yet another level of detail. Also, the reader may have noted that much additional information could have been included in the network to extend its scope. For instance, we could have indicated that the sun is a star (sun $\xrightarrow{\text{ISA}}$ star), that space is vast (space $\xleftarrow{\text{property}}$ vastness), that the sun's radiation includes ultraviolet rays (radiation $\xrightarrow{\text{HAP}}$ ultraviolet rays), that the earth is a small planet (earth $\xrightarrow{\text{ISA}}$ planet $\xrightarrow{\text{property}}$ small), that the earth also produces its own heat from its interior but that this heat is only one 25 thousandth of the heat absorbed from the sun (earth $\xrightarrow{\text{HAP}}$ interior $\xleftarrow{\text{agent}}$ produces $\xrightarrow{\text{object}}$ heat $\xleftarrow{2.5 \times 10^4}$ radiation_2), and so on.

In a sense, there is a trade-off between the level of detail (i.e. the "resolution") and the scope (i.e., the "field of vision") of information included in a network. The broader the"field of vision"we wish for a network the less "resolution" we can provide. Similarly, the higher the resolution of our network (i.e., the "finer grained"), the more restricted will be our field.When representing a single proposition we can do so with extreme detail. When representing a whole course of study we will sacrifice much detail in order to capture the scope of the course. Most representations of knowledge will fall somewhere in between these two extremes.

Episodic and semantic aspects of memory do not exhaust the kinds of infor-

mation that can be stored in LTM. Norman and Rumelhart (1975) point out that people also have knowledge of procedures and that this "process" knowledge can be stored in LTM and, once stored, can be accessed and operated on. Representational systems have been worked out by these researchers for this type of knowledge. Furthermore, some researchers believe that people store images in LTM (Paivio, 1971), although this is an issue which has generated some interesting debates.[8]

This diversity of approaches to the study of LTM and the lack of consensus on how to represent the information stored in LTM stem from differences in the particular phenomena of interest to the researcher. Different researchers research different questions, and, thus, deal with different data requiring different modes of representing those data. Knowledge of stories (Rumelhart, 1976), paragraphs (Meyer, 1974), procedural steps (Norman and Rumelhart, 1975), faces (Norman and Bobrow, 1976), rooms and objects (Minsky, 1975), sequences of experienced events (Schank, 1975), class concepts (Quillian, 1969; Lindsay and Norman, 1977), emotions, and sounds each place different demands on a representational system.

Although all the above aspects of an individual's data base may be relevant to some curriculum developers and researchers, the focus of the remainder of this paper is on semantic memory and semantic networks for representing conceptual knowledge. This focus is based on the assumption that schools and colleges have as one of their primary purposes to transmit organized subject matter, i.e., the concepts and propositions of various disciplines of knowledge. Semantic networks appear to have great potential for studying the structure of such conceptual knowledge. Researchers and developers more interested in

schooling as experiences to be remembered, as visual or auditory percepts to be decoded, stored, and utilized, as procedural steps to be learned, or as motor skills to be mastered, will probably find approaches other than the ones described in this paper most useful.

C. Validity of Knowledge Representations.

Semantic networks such as that depicted in Figure 2, above, represent the "structure of knowledge." This knowledge structure may be the knowledge of a student (i.e., cognitive structure organized into schemata), the content of a set of instructional materials (i.e., content structure), or the knowledge embodied by a discipline (i.e., the structure of a discipline). Likewise, network representations of knowledge can be derived from three sources: from students' free recall, response to questions, or other utterances (thus generating a representation of cognitive structure), from analyses of instructional material (thus generating a representation of content structure), or from a course developer's expert knowledge of his subject matter (thus generating a representation of the structure of knowledge in a discipline). Depending upon the source of the network, claims regarding epistemological and psychological validity of the networks will be made and can be tested.

In the case of the course planner attempting to represent the propositional structure of a subject matter area, the concern is with the epistemological validity of the network. Rather than ask a panel of experts in his area to assess the validity of the network directly, it would seem more feasible to ask experts to judge the validity of the set of propositions derived from or at least congruent with the network. Experts could be asked to judge the truth value of each statement, to judge each statement's relative significance

to the discipline, and to examine the entire list for any significant omissions. Summaries of several highly respected textbooks in the area could be used as a second check on the validity of the network.

Assessing psychological validity of a semantic network is a bit more complex a problem. One approach to assessing psychological validity has been to ask students to make judgments regarding relationships between concepts and to determine if their reaction times to the questions correspond to the "psychological distance" between the concepts (i.e., the number of lines between nodes that must be traversed in order to make a judgment). For example, Figure 5, below, depicts a semantic network used in the research of Collins and Quillian (1969). Figure 6, below, presents a graph showing the relationship between reaction time and psychological distance for the question: "X is a Y -- True or False?" where X and Y are concept labels of varying positions (i.e., varying distances) in the network. As Figure 6 shows, the psychological validity of the semantic network in Figure 5 seems to be supported by the experiment.

Lest the reader assume from this one study that people store semantic information in subset-superset hierarchies, the research of Rosch(1973) and Rips, Shoben and Smith (1973) should be mentioned. These researchers have shown that many judgments of class membership are not made by tracing relationships within conceptual hierarchies. Rather, most people compare instances with prototypes (i.e., good examples) of the general concept. For example, judging whether a particular species is an animal involves comparing a par-

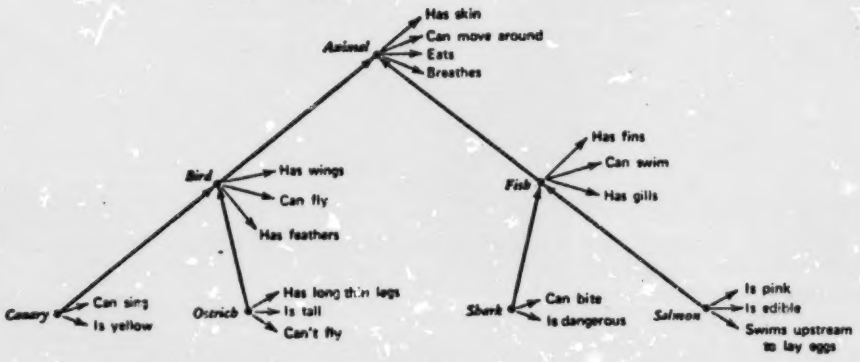

Figure 5. Illustration of a hypothetical memory structure for a three-level hierarchy. (From Collins and Quillian, 1969 and reproduced in Rumelhart, 1977, p. 231.)

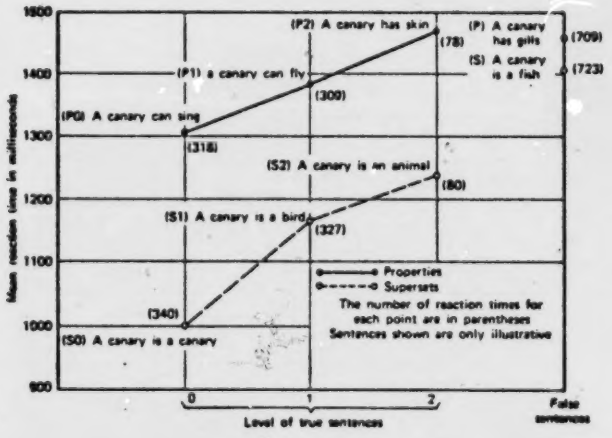

Figure 6. Reaction times in a sentence verification task as a function of the level of the queried property from the subject term in the hypothetical hierarchy that is illustrated in this figure. Reaction times to fault sentences are illustrated in the far right of the figure. (From Collins and Quillian, 1969 and reproduced in Rumelhart, 1977, p. 232.)

ticular example of that species with a prototypical animal, in other words, a judgment of "typicality." Things (e.g., wolves) that look like the prototypical animal (usually something like a horse or a dog) are more readily judged to be animals than things that differ substantially from the prototype (e.g., spiders and sponges). This discussion is not intended to resolve these two conflicting research findings. It is only intended to point out the complex nature of the psychological validation problem and to suggest some possible empirical approaches to the problem.

Issues of psychological validity of network representations are, in part, issues in evaluating what people actually know or learn. This perspective on the problem is discussed in the last section of this paper. In that section I discuss the use of test questions, exercises, clinical interviews and free recalls for evaluating what a student learns from instruction. These strategies also serve as potential approaches to the psychological validation of network representations of knowledge.

Part II

Curricular Applications of Cognitive Science

Studies of the human information processing system have yielded models of the cognitive structures and processes necessary for intelligent human functioning. These studies have provided new insights into the cognitive requirements of significant school-related tasks. As a result, curriculum researchers currently have available a technology for examining in great detail what is involved in answering questions (both on tests and during instruction), in classroom activities, and in understanding instructional materials (e.g., reading a textbook). Likewise, curriculum developers now may approach tasks of expressing curricular objectives, analyzing the structure of knowledge in a discipline, evaluating student learning and describing the content included in a text with a degree of detail never available to them before. Let us, thus, discuss the implications of cognitive science for curriculum research and development. This discussion is divided into discussions of discipline analysis, cognitive objectives, content organization decisions, content analysis, and evaluation of student learning.

A. Discipline Analysis.

Mapping out major concepts and their relationships has been recognized as a useful technique in curriculum planning (Weil and Joyce, 1978, pp. 204-214; Gagné and Briggs, 1974; Novak, 1977; Senesh, 1973; Posner and Rudnitsky, 1978). However, previous attempts have suffered from several limitations. Novak's (1977) and Weil and Joyce's (1978, pp. 204-214) extensions of Ausubel's approach to curriculum structure through concept mapping have relied exclusively on class

membership relations among concepts. Gagné and Brigg's (1974) work has relied strictly on prerequisite relationships among skills, thus obscuring the diversity of relationships that render any skill a prerequisite of another.[9] Senesh (1973) and Posner and Rudnitsky (1978) include a consideration of relationships among concepts in their conceptual maps but do not provide explicit procedures for deciding what precise relationships should be included in the maps, how to relate the major propositions of a discipline to the concept maps, and how to decide which relationships are necessary and sufficient to include. Nonetheless, semantic networks can be considered an extension of these previous efforts with an increased emphasis on specifying precisely the diversity of relationships between the major concepts of a discipline.

By depicting the conceptual structure of a discipline with semantic networks and by working back and forth between these networks and lists of concepts and propositions, several insights are likely to occur that would not be likely to occur without the use of network representations. Through the use of networks, the planner is able to check his lists of propositions and concepts for comprehensiveness. Implicit relationships between concepts may come to light thus suggesting additional propositions. Concepts useful for helping students see the coherence of the subject matter may become clearer. Concepts necessary for stating important propositions may be identified. Connections between two seemingly unrelated schemata may be found.

Constructing a network that is consistent with a set of concepts and propositions is an exercise that helps the planner "unpack" the conceptual structure of the discipline. (Gowin, 197) It helps give the planner increased "knowledge of his knowledge" (Gowin, 1977), something which distinguishes the planner from the subject matter specialist.

Another approach to representing the structure of knowledge in a discipline is to develop representations of the cognitive structure of experts in a particular subject matter. This approach is based on the assumption that disciplines of knowledge exist in the minds of experts and, thus, can be analyzed using psychological approaches to the problem of knowledge representation. The section on evaluation of student learning (below) presents potential techniques for assessing any person's state of knowledge, whether student or expert.

B. Cognitive Objectives.

Debates about educational objectives have typically formed between advicates of behavioral objectives and advocates of general objectives.[10] From the writings that have been generated by this debate one could easily be led to conclude that the choice is simple enough: either we state objectives in terms of measurable observable beahviors (which the critics of behavioral objectives claim leads to trivializing the curriculum) or we state them in general often vague terms (which we are told by critics of general objectives leads to imprecision and lack of clarity).[11] However, the recent developments in cognitive science in general and the work of Greeno (1976) on "cognitive objectives" in particular suggest a way out of this dilemma. "Cognitive objectives" (a term I will now use to refer only to Greeno's concept, not to be confused with common usage of the term stemming from Bloom's taxonomy) share with behavioral objectives the concern for precision, clarity and specificity. However, they do not share the behavioral-objectives ad-

vocate's insistence on observability, his reliance on simple declarative statements (e.g., "the learner will...") with acceptability criteria for verbs and objects, nor his insistence on specifying conditions and criteria of the expected behavior (à la Mager). As Hayes (1976) points out:

> To specify a behavioral objective for instruction, we state a particular set of behaviors we want the students to be able to perform after instruction, e.g., to solve a specified set of arithmetic problems, or to answer questions about a chapter in a history text. To specify cognitive objectives we state a set of changes we want the instructions to bring about in the student's cognitive processes, e.g., acquisition of a particular algorithm for division or the assimilation of a body of historical facts to information already in long-term memory. (pp. 235-236)

Greeno's work demonstrates that recent developments in cognitive science have contributed both a deeper understanding of cognitive processes and structures which underlie the competent performance of tasks typically encountered in school subjects, and also techniques sophisticated enough for representing these processes and structures, so that curriculum planners can specify the intended learning outcomes. The examples Greeno presents cover a fairly broad range from algorithmic skills needed to compute fractions, to problem solving procedures and knowledge structures necessary to construct geometric proofs, to the understanding of auditory psychophysics necessary for answering complex questions in the psychology of perception. The last of Greeno's examples is particularly interesting since it demonstrates the use of techniques from cognitive science for specifying in rather precise terms what it means to understand a set of concepts and propositions. By specifying the complex network of interrelationships among concepts it des-

cribes in sufficient detail the intended schema that students in this college course are expected to have and the role of this schema in the answering of classroom or examination questions that require this knowledge. Figures 7, 8 and 9, below, represent the data base for the physics of sound, the anatomy of hearing, and auditory psychophysics, respectively.

Greeno's work demonstrates the utility of considering problems in stating objectives to be a special case of the more general problem of representing knowledge. Further he shows the extent to which our increased understanding of cognitive structures and processes can contribute to the precision and comprehensiveness with which we can represent those aspects of cognitive functioning we, as curriculum planners, wish students to acquire as a result of instruction. Finally, he attempts to relate these internal cognitive structures and processes to the capabilities of students in performing cognitive tasks, such as answering complex questions.

C. Content Organization Decisions.

The curriculum planner is often faced with many organizational decisions. These include decisions whether or not to treat two topics separately or to attempt to present the topics in an integrated fashion. For example, suppose a person is planning a course on measurement. He constructs separate networks for the topics of content validity and predictive validity. He must then decide whether these two topics can be related. He can examine the two networks for common concepts, which he may want to present, before discussing the concepts specific to each topic. Or he might try to integrate totally the two topics by searching for ways to combine the two networks. Difficulties the planner has in integrating two semantic networks probably parallel to some

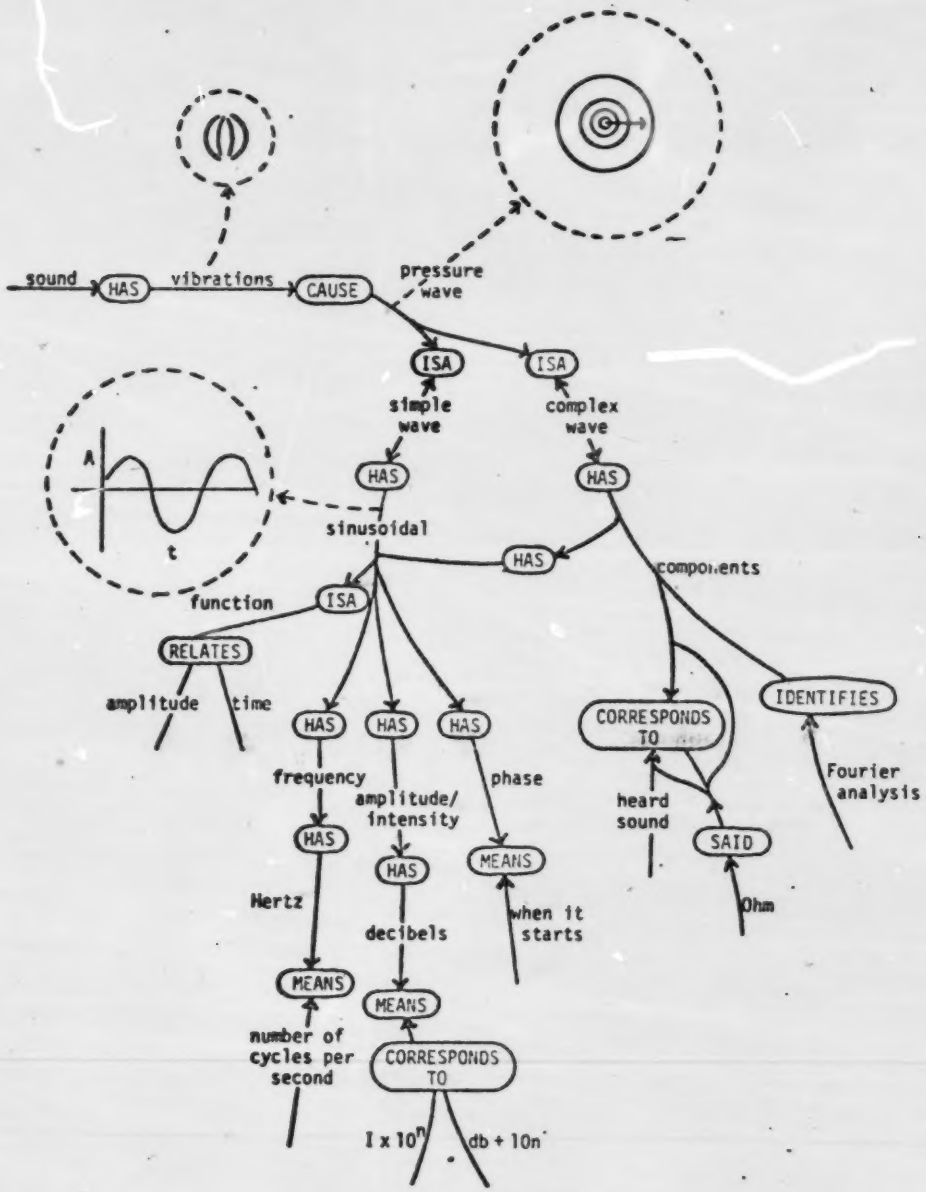

Figure 7. Network of propositions for physics of sound. (From Greeno, 1976, p. 151.)

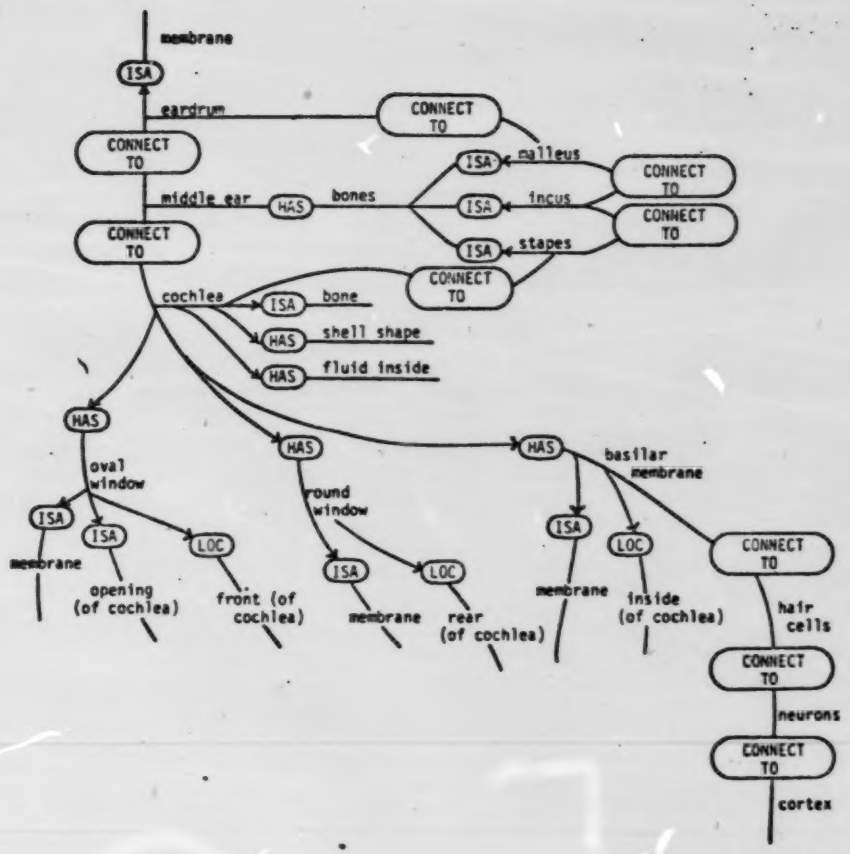

Figure 8. Network of propositions for anatomy of hearing. (From Greeno, 1976, p. 152.)

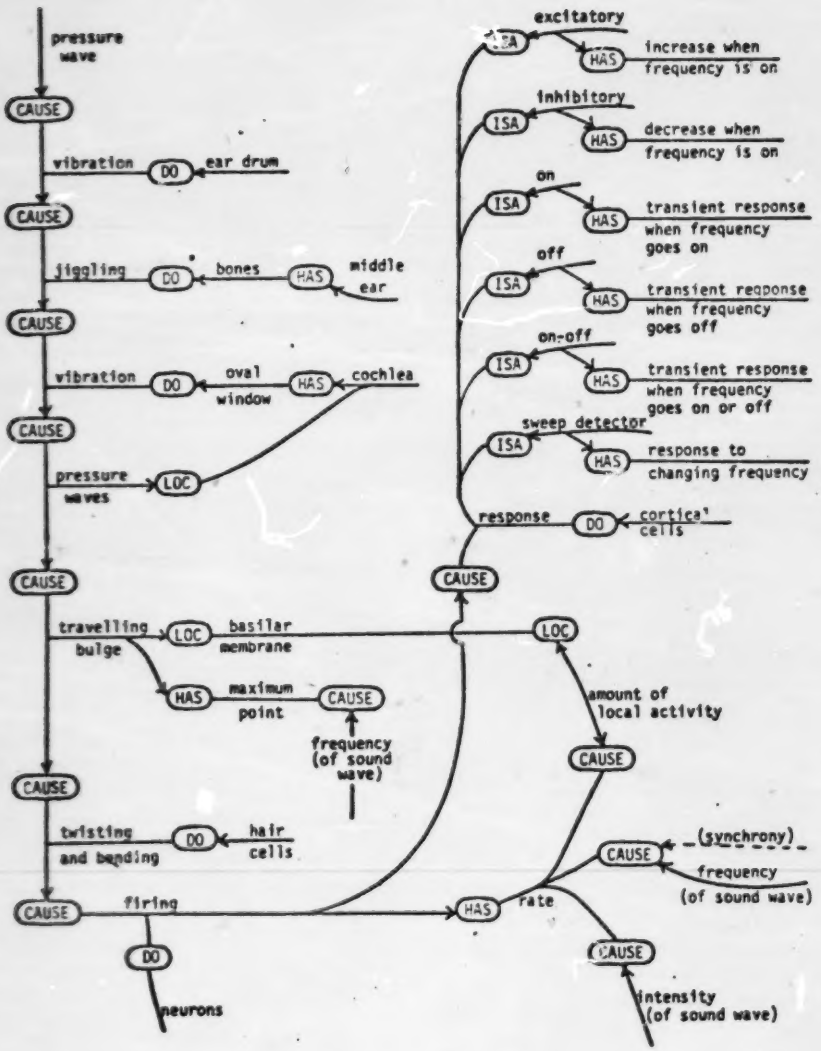

Figure 9. Network of propositions about events that occur when a sound is heard. (From Greeno, 1976, p. 154.)

extent difficulties students will have in integrating two schemata. Similarly difficulties the planner has in finding ways to relate a new concept to a given semantic network parallels difficulties students will have in learning the new concept meaningfully. After all, meaningful learning entails in part the integration of new concepts into an existing schema in long-term memory. Network construction obviously does not make planning decisions for the course designer but the networks certainly serve as one guide in these sorts of decisions.

D. Content Analysis.

Semantic networks can be considered a way of depicting the conceptual structure of a set of instructional materials (e.g., a textbook). As such, semantic networks represent a useful technique for content analysts. Different instructional materials can be compared on the basis of the content they are teaching and how that content is organized. The content structure of a textbook can be compared with the structure of knowledge as viewed by experts in the field. A textbook which lacks a student workbook can be analyzed and, based on this analysis, student activities can be designed to supplement the text. A person planning a new course can analyse the content of courses that are considered prerequisite to the new course and those that are to follow it in order to provide for continuity and cumulative learning. Research can be undertaken regarding the extent to which the content structure in a text affects the cognitive structure of students.[12]

For each of these uses, the content analyst may first attempt to produce a list of the major concepts and propositions taught in the instructional materials and a summary (or a set of summaries) of the content. Working back and forth between these lists and summaries, the analyst can then develop a semantic network consistent with these other representations.

The network he produces depicts the complex interrelationships among the content elements in a parsimonious form. It is the capability to represent conceptual complexity in a parsimonious manner that gives semantic networks their utility in content analysis as well as in their other applications.

Another area for content analysis is the activities of the classroom. For example, educators attempting to individualize activities for students need to know what it is about particular activities that make them more suitable for one student than for another.

> To discover this, it would be necessary to analyze the activity in a theoretically meaningful way. We do not know yet how to do this. I suggest, therefore, that careful empirical, theoretically guided research on the relationship between particular structural features of activities and their detailed outcomes, should be a high priority for the program of research contemplated.
>
> (Walker, 1978, p. 8)

Of course, it is granted that the content structure of activities is but one of several structures (e.g., there is also the social structure). However, techniques and insights from cognitive science present a presently untapped resource for analyzing and representing the content structure of classroom activities. Cognitive science offers one set of techniques for use in research into the effects of various forms of classroom activities. Such research could begin by "an analysis...of the content structure of the activities included as well as their performance and social structure, and then...alternative versions [could] be designed differing in ways considered pertinent to the particular investigation." (Walker, 1978, p. 14)

E. Evaluation of Student Learning.

If, as Greeno suggests, a semantic network represents the schemata students are expected to develop as a result of instruction, they can be

used in evaluation efforts. Test questions can be constructed using semantic networks as guides to the content to be covered in the test. Or, similarly, the content validity of a set of questions can be ascertained with reference to a network representation of the content.

In some of our research at Cornell, clinical interviews have been conducted with students prior to instruction in order to determine what they already know (as Ausubel, 1968, suggests). Then after instruction has been given in light of this knowledge, additional interviews are conducted in order to determine what students have learned, both as a result of and in spite of instruction. In these interviews, an earlier form of semantic network has proven to be an invaluable aid in directing the interviewer to probe for possibile misconceptions (Pines, 1977; Rowell, 1978)

Another approach that may prove useful employs printed self-instructional materials which ask the subject to answer questions in writing and to complete exercises. The subjects' written responses to questions and exercises as well as summaries of material requested during instruction might be analysed to reveal the subjects' changing cognitive structure. An important methodological strategy here is to use the mistakes students make as clues to their state of knowledge at the time the mistake is made. Although a good deal of inference is required, subject matters with more formal structures (such as mathematics) may permit such inferences with a relatively low risk of misinterpretations.

In these techniques and, in fact, in most evaluation settings, student answers to questions are a prime source of information regarding what students know. However, the model of human information processing presented earlier suggests the care that must be given to the evaluation task. Inferences

regarding students' data base from responses (or lack of responses) to questions are, at best, risky. Any questions, even simple ones, present a whole set of cognitive tasks and therefore cannot be interpreted as a straightforward determination of what is stored in LTM.

Walker is probably correct in stating that

> [w]hen we understand the test situation itself, we shall be able to design and redesign measures appropriate to different outcomes. My own judgment is that we will not understand the other activity structures [test-taking being one such structure] and their effects until we understand those involved in testing. I would therefore place research on the structure of the test situation at the top of my priority list.
> (Walker, 1978, pp. 6-7)

Now, cognitive science has yet to produce anything resembling the kind of "theory or model of achievement" Walker claims we desperately need (1978, p. 52). But recent studies of question-answering tasks provide the beginnings for such work.

A synthesis of ideas from several cognitive scientists (particularly Greeno, 1976, Lindsay and Norman, 1977, and Scragg, 1975) yields the following outline of some of the cognitive tasks required for answering a typical classroom or examination-type of question.

1) The question must be comprehended. This requires considerable knowledge of the subject matter, syntactical rules, and a verbal lexicon for decoding the question (all in LTM), and the use of that knowledge for constructing an interpretation of the information given in the question.

2) In order for the student to be able to generate an answer that provides an adequate explanation, the student must have learned what counts as an explanation of something. Adequate explanations must have certain kinds of elements and must be organized according to certain rules. These rules must also be part of the student's data base (i.e., LTM).

3) The student must also decide whether or not he can answer the question and whether or not it is worth the bother. These are the functions of the monitor system.

4) Once the monitor decides that a search is likely to be fruitful and the student's schema for "explanation" is activated, a search of LTM can be conducted by the interpretive processes for relevant information.

5) Obviously different sorts of questions require different sorts of searches of the data base, different sorts of information in the data base, and different manipulations of information by the interpretive processes once found within the data base.

Yes-no questions often (though not always) require only direct retrieval of information or simple deductions. For example, Figure 10, below, depicts a portion of what a hypothetical student knows about ostriches.

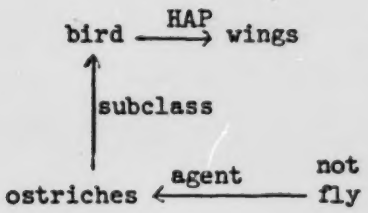

Figure 10. Schema for "ostriches" as learned by a hypothetical student.

The question "Can ostriches fly?" merely requires checking to see if one of the propositions that apply to ostriches concerns flying. The question "Do ostriches have wings?" requires the following deduction: Bird have wings. Ostriches are birds. Therefore, ostriches have wings.

What-if questions require tracing through an entire network examining alternative paths at various nodes in the network, holding the consequences of following alternative paths in STM while following still other alternative paths -- all this while still not losing one's place in the network. No wonder that the examination of alternative courses of action is a strenuous task even with external aids to STM (such as pencil-and-paper). Clearly, there is more to answering what-if questions than having the relevant knowledge in LTM.

Comparison questions such as "How do ostriches differ from canaries?" require comparing memory schemata, in this case the ostrich schema (above) and the canary schema in Figure 3. This comparison is performed by the interpretive processes.

"Why?" questions probably present the greatest problem for the human

information processing system. For example, "Why did the beaker get hot?" may be answered by giving any of the following explanations:

a. Because the chemical reaction in the solution inside the beaker generated heat which was transferred to the glass surrounding the solution.

b. Because the person didn't put ice cubes in it.

c. Because the person was making something in it.

d. $HCl + NaOH \rightarrow H_2O + NaCl$ + heat.

e. Because the solution in it started to "smoke."

f. A chemical reaction.

g. Magic.

It is likely that deciding what is meant by "Why?", that is, what will count as an answer is probably more difficult than answering the question,once this is known. As mentioned previously, these sorts of decisions are a function of the monitor system.

These sorts of questions have been discussed in order to give the reader the flavor of recent analyses of question-answering by cognitive scientists. Most of these analyses point out that question-answering tasks (even very simple ones) are more fruitfully viewed as problem solving activities rather than simply retrieval of stored information. Lindsay and Norman, 1977 provide a useful discussion of this issue focusing on the question "What side of the door was the doorknob of the house you lived in two houses ago?" They point out that attempts to answer such a question reveal the reconstructive nature and problem solving characteristics of even "recall" questions.

6) Once relevant information is located, constructed and/or reconstructed it must be manipulated(again by the interpretive processes) in order to construct an explanation.

7) Once an explanation is constructed it must be encoded into language employing the same syntactical rules and verbal lexicon (from LTM) used by the student in decoding the original question.

8) Finally, motor skills of expression are used to communicate the "answer."

Now this outline is nowhere near detailed enough to account for all the tasks involved in answering a question. But even this simplified version suggests the complexity of the process and the number of factors that may intervene between even a simple question from a teacher or test and the student's answer. (I have not even mentioned such other factors as attention and cooperation.) Successful performance depends on a great deal more than just having the appropriate knowledge in LTM. Answers to questions are a high inference measure of what a person knows (i.e., what information is in LTM), and yet they are our primary means of evaluating knowledge. As Strike (1977) put it: It's a bit like trying to determine the economy of New York City by watching the traffic flowing across the bridges -- tricky and complex but not impossible. Clearly, great care ought to be taken in drawing our inferences about cognitive structure from student utterances of any kind. However, the more adequate our theoretical model concerning the cognitive structures and processes involved in answering questions, the better will be our inferences regarding what a person knows from his responses to questions. As Strike (1977) points out, such a model also helps in identifying the nature of the assumptions made in inferring anything about cognitive structure from the stimulus (i.e., the question) or the response and "in tracking down and eliminating alternative accounts." (p. 48)

One approach to questioning as a method of evaluating student learning developed at Cornell involves the use of open-ended questions in conjunction

with semantic networks and clinical interviews. We have been asking students rather open-ended questions and then transforming the students' responses into semantic networks. For example, we have asked students to judge the truth value of a set of propositions (derived from our semantic network representations of the subject matter), then to explain why they believe each statement to be true or false. It is these explanations that we have transformed into semantic networks. This approach has enabled us to focus our evaluation on just those propositions that might reveal the misconceptions or missing relationships in which we are interested. The semantic networks that result allow us to compare students qualitatively and to compare each student's cognitive structure with that of an "expert" and with the content structure of the instructional materials. Of course, just because a student fails to mention a particular relationship does not mean that he does not know about it. Thus, we have used this type of instrument in conjunction with clinical interviews to probe further on specific concepts and propositions that are still problematic. This sort of two-stage evaluation (i.e., paper-and-pencil test followed by clinical interviews) appears to be an economical but fairly valid approach. However, much more refinement and validation of our methods is needed.

In order to explore as exhaustively as possible what a person has learned from instruction, free recall has proved to be a very rich source of data (McConkie, 1977). A relatively short recall can provide evidence of a large number of concepts and relations having been retained. However, a primary limitation of this method is the fact that a person's ability to retrieve information from a large set is definitely limited. Successive attempts to recall the same information tend to produce equivalent recall levels, but different information tends to be included on successive attempts

(Tulving, 1967 ; Meyer and McConkie, 1973).

The clinical interview mentioned earlier provides for a mix of question-answering approaches and free recall strategies. A general question can be asked and then followed up with more specific questions to probe for additional knowledge in areas not originally included or which were initially unclear (Pines, 1977; Pines et al, 1978). The problem with this method is the interviewer's limited memory capacity. It is difficult to remember, to code and to review just what parts of a substantial body of knowledge has been included in an interview. Thus, the follow-up questions may not be the most appropriate, and records may not be complete and accurate.

So that we might capitalize on the focus provided by question-asking, the rich data source provided by free recalls, and the probing quality of the clinical interview we are attempting to develop an automated clinical interview at Cornell. The computer can be used both to keep records of what a person has shown evidence of knowing and to select the most appropriate follow-up questions, continually becoming more and more specific in the questions selected and developing a growing representation of what the student knows. Having a relatively complete indication of what the student knows within the domain of interest could be a valuable research tool in understanding the effects of different types of curricular approaches and could also be the beginning of an interactive testing system in which instructional decisions could be made on the basis of what the student shows evidence of knowing.

If we are more interested in how students utilize what they know than in what concepts they have learned (i.e., the control processes rather than the data base), we might attempt to collect information directly regarding the way they go about solving problems. One approach to collecting

this kind of data is to have students think aloud as they solve problems. The students' "thinking aloud protocols" (Newell and Simon, 1972) can then be analyzed and problem solving strategies identified. Such studies have already been carried out in organic chemistry (Atkin, 1977), chess, logic and cryptarithmetic (Newell and Simon, 1972). These studies have yielded both substantial insight into the kinds of strategies people employ and also sophisticated techniques for representing the steps followed by problem solvers.

One final area of application in evaluation and research concerns the relationship between what children learn in schools and how they utilize what they learn in "real life" situations -- the so-called "life uses of schooling" (Broudy, 1972). The National Assessment of Educational Progress recently reported that although children are learning as much information in many subject areas as they used to, their scores on application-type items have fallen dramaticlly. In order to find out why this decline in ability to apply knowledge has occurred, researchers first need a reasonable model of how school-learned information is applied in the solution of "real-life" problems. If one classifies this research area as a subclass of research on how the information in an individual's data base is related to his ability to solve problems and make decisions, then one can bring to bear on this research many of the techniques, concepts and principles generated by recent work in cognitive science. All it takes is an interest in the area by persons with the requisite background.

Part III

Concluding Remarks

As participants of the two conferences were quick to point out, substantive recommendations for education based on research in cognitive science are few in number, and when they are made appear vague and commonsensical. For example, Norman, Gentner and Stevens (1976) concluded with such recommendations as follows:

> Introduce the general framework for the material that is to be learned.
> Build upon the general knowledge that previously existed...
> The student should know how to evaluate and modify his schemata.
> (p. 195)

The first two of these recommendations certainly do not strike one as being revolutionary. As a matter of fact they sound very similar to ones made by Ausubel 15 years ago.

What then is the contribution thus far of cognitive science? Farnham-Diggory (1976) sums up the situation well: "In summary we can say that our modern technological and theoretical capacity to represent changing conceptual states is a major advance...." (p. 229-30) These advances in the representation of knowledge, particularly in the development of semantic networks, permit parallel representations of the structure of knowledge in disciplines, cognitive structure of experts, content structure of materials and activities, and cognitive structure of students prior to, during, and subsequent to instruction. Once these techniques have been further refined for these areas of application, researchers can compare these aspects of knowledge. Such comparisons can serve as a basis for addressing questions regarding effects of different content structures on cognitive structure, the role of what a student already knows on what he learns from instruction, the way students develop and modify schemata and how these processes are influenced by instruc-

tion, and the relation between the structure of knowledge in disciplines and the content structure of materials and activities, to mention just a sampling of significant areas of research made feasible by technological developments in the representation of knowledge.

To the extent that curriculum problems are considered to include those having to do with the content of schooling and with the organization of that content, an increased capacity to represent that content and to specify how knowledge is utilized in the performance of tasks promises to have important technological implications for curriculum developers, evaluators and researchers. To date, this potential has been only partially realized.

Footnotes

1. Ausubel, 1968 and Farnham-Diggory, 1972 represent two early attempts.

2. The first conference was the Tenth Annual Carnegie Symposium on Cognition held June, 1974 in Vail, Colorado, under the auspices of the Department of Psychology at Carnegie-Mellon University. The second conference was The Conference on Schooling and the Acquisition of Knowledge held November, 1975 in San Diego.

3. However, see Neisser, 1976 and J. Anderson, 1976 for arguments to the contrary.

4. See Luria's (1968) case study of a pathology based on this limitless capacity.

5. Neisser, 1976, makes a similar point.

6. See Schank (1975) for arguments against this distinction and, more particularly, against the notion of semantic memory.

7. One of the most useful systems for representing semantic and episodic memory and the one on which this paper is based was originally developed by a group of researchers at the University of California, San Diego, known as the LNR Research Group (after Peter Lindsay, Donald Norman and David Rumelhart). Norman and Rumelhart (1975) provide a full description of the LNR system. Since their system was not designed for curricular or instructional applications, I have taken great liberties in modifying their approach in order to make it more amenable to my purposes. See Frederiksen (1975), Kintsch (1974), J.R. Anderson (1976), and Anderson and Bower (1973) for other representational systems that bear some resemblance to the LNR system but with significant differences.

8. See, for example, the debate between Pylyshyn, 1973 and Paivio, 1975.

9. See Strike and Posner, 1976 and Posner and Strike, 1976, for critiques of these approaches.

10. See, for example, Eisner, 1969 and Popham, 1969.

11. See Macdonald-Ross, 1973 and Strike and Posner, 1974, for exceptions to this highly polarized framework.

12. See Frase's 1975 review of research on this question.

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